Martian magnetization—preliminary models

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Data being collected by the Mars Global Surveyor (MGS) are providing a fascinating and unexpected image of the magnetic field of Mars. Early results from Mario Acuña, principal investigator of the magnetometer experiment from NASA's Goddard Space Flight Center, and his coworkers showed magnetic stripes over parts of the southern hemisphere evocative of those in the ocean basins on Earth that are caused by the magnetization of new crust generated at spreading ridges in an alternating polarity field. This suggests that plate tectonics may have occurred on Mars, and implies that the Martian dynamo reversed during its short life, which must have encompassed the creation of new crust. Another pointer to tectonic activity or at least structural events is the truncation of magnetic features over the Valles Marineris and Ganges Chasma.

In this article, we present further suggestions of both magnetic reversals and tectonic activity on Mars from preliminary results of an inversion of MGS data for models of crustal magnetization. We find patterns of magnetization inclinations reminiscent of a triple junction, and reversed magnetization poles.

One of the first surprises from MGS was the strength of the Martian magnetic field. Dynamo action ceased in probably the first 0.5 billion years of the planet's history, so what we observe today is the remanent magnetization generated during that period and locked into the crust. During the aerobraking phase of the mission, when MGS was as close as 120 km to the surface, fields in excess of 1500 nT were measured. We rarely observe such large anomalous remanent magnetic fields on Earth even in aeromagnetic surveys a few hundred meters above the terrestrial surface. At spherical harmonic degrees beyond 14 or so (wavelengths shorter than ~2760 km), where we believe the terrestrial field has a negligibly small contribution from geodynamo action, there is about two orders of magnitude more power in the Martian field. There are a number of possible explanations for this. Such short-lived dynamo action may have been more energetic, generating higher strength magnetizing fields while it was in operation. There is thought to be more iron in the Martian than terrestrial crust, so we might expect higher magnetizations to result from the same magnetizing field strength. The mineralogy could be different, again potentially leading to larger magnetizations. But although the Martian surface, with planetary radius about 3393 km, is closer to its core (radius between 1520 km and 1840 km) than in the terrestrial case, the attenuation of the field strength depends on the ratio of radii of the planet to its core, not the distance between them. This ratio is larger for Mars (~2.0) than for Earth (1.8), leading to greater attenuation.

The data inverted to obtain the magnetization models presented here are vertical component magnetic field measurements collected in two phases of the mission, at altitudes between approximately 100 and 600 km, and provide almost complete coverage. Vertical component data are less contaminated by external magnetic fields (due to solar activity) than the horizontal components. To reduce the data scatter and the computational effort involved in inversion, and because we cannot resolve features less than 100 km or so (the minimum altitude at which measurements have been made), the data have been averaged into 1° bins (1° represents approximately 60 km on the Martian surface). We only included bins containing more than one data point, giving a statistical measure of uncertainty. This reduced the data set to 49 635 points. Data were normalized to unit variance using these standard deviations. There are several images in the literature of data sets collected earlier in the mission, such as that by one of us (MEP) and coworkers at Goddard Space Flight Center, on which key features referred to here are labeled. Mars shows a large contrast between strong magnetic fields in the southern hemisphere and relatively weak fields over most of the northern hemisphere. The dichotomy separating the two regions also divides the planet into a much higher elevation, more heavily cratered, southern hemisphere and a lower, flatter northern hemisphere, as seen from the laser altimeter (MOLA) images. The northern hemisphere contains a significant thickness of extrusives and sediments blanketing much of the surface. These younger rocks were formed after the Martian dynamo switched off, and are therefore nonmagnetic. However, the underlying older rocks must also be less magnetic than those in the southern hemisphere to explain the low field strengths measured.

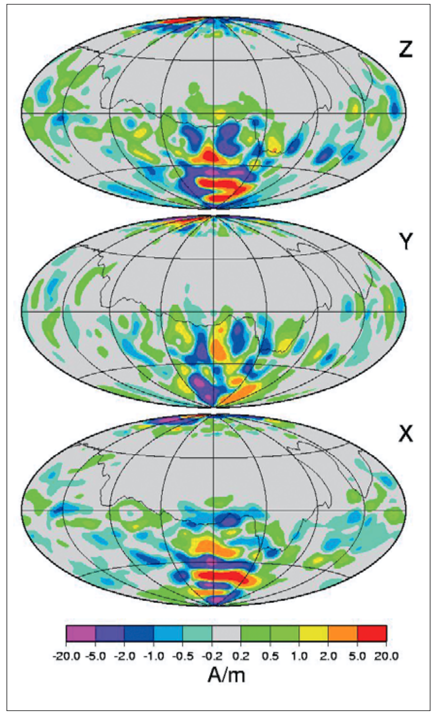

Figure 1. Global maps (Hammer projection) of a magnetization model for Mars produced by our method. The north (X), east (Y) and vertically downward (Z) components of magnetization are in A/m (color scale). Note the contrast between the weakly magnetized area to the north of the dichotomy (solid line) and the more strongly magnetized area to its south. The central meridian is 180° longitude.

Our inversion method solves for a continuous distribution of magnetization within a layer of constant, specified thickness (40 km, based on estimates of crustal thickness from variations in the topography and gravity field). Inversions of terrestrial satellite data have indicated that the effect of varying the thickness is that the model magnetizations adjust such that the vertically integrated magnetization is constant. This is what we would expect—satellites "see" the magnetized crust as a thin layer and are unable to resolve depth variations. We feel compelled to remind the reader about the usual ambiguities that exist when dealing with specific modeling problems like these. Unique solutions are obtained by requiring that our models have minimum average magnetization strength, for a given fit to the data.

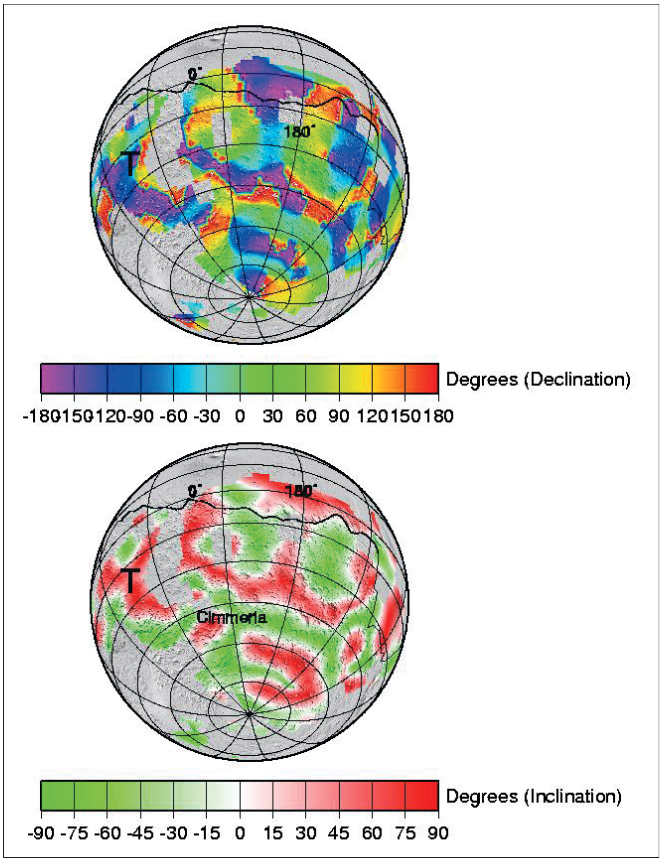

Figure 2. Magnetization declination (top) and inclination (bottom), plotted only where magnetization strength is sufficiently large for the angles to be well determined (color scales), superimposed on the MOLA topography (gray shaded relief). The south pole is toward the bottom of the map; the equator and 180º longitude are labeled. T marks the center of the best developed triple junction-like feature. The thick solid line is the dichotomy boundary. Orthographic projection, with the more strongly magnetized hemisphere shown.

Within this framework, we solve for the model coefficients, a daunting computational task, because the design matrix relating them to the data has almost 2.5 billion elements! Fortunately, most elements are negligibly small, and we can therefore regard it as numerically sparse. Based on previous studies, we retained the largest 0.87% (approximately 21 million) elements of the design matrix, treating the remainder as if they were zero, and used the iterative conjugate gradient algorithm to determine the model coefficients.

The relative importance of fitting the data and minimizing magnetization strength is controlled by a damping parameter. There is a direct analogy between models produced by our method and damped equivalent source magnetization modeling: Both have minimum average magnetization strength. Equivalent source modeling is a common way to produce magnetization models: The volume of crust to be modeled is divided into blocks, with a magnetic dipole at the center of each. Usually, the directions in which the dipoles point are specified, leaving their strengths to be deduced from the data. Magnetization is then deduced by normalizing by the volume of the block.

Figure 1 is an example magnetization model calculated using our method. The north (X), east (Y) and vertically downward (Z) components are plotted. Note that we infer the full magnetization vector, although only vertical component magnetic field data were inverted. In our models, vertical component magnetization is highest, but there is significant power in the horizontal components. Figure 1 shows a strong magnetization contrast across the dichotomy. North of the dichotomy, magnetic features are relatively isolated, and we can see a direct association between features of the magnetization model and features in the original data. South of the dichotomy, the magnetic field is significant almost everywhere, and is modeled as continuous, strong magnetization. A puzzling feature of our model is the large magnetization in all three components over the North Pole. The data show only slightly enhanced amplitudes in this region, which may be caused partly by external field contamination. Future studies will investigate the models in this region. However, the models elsewhere look to be a good representation of the data. We have also compared the vertical component of our models with vertical dipole equivalent source models, and agreement is encouraging.

Ideally, we would choose the damping parameter to achieve a (normalized) misfit of unity, but none of our models fits the data that well. This is probably because of unaccounted for noise in the data. Over a wide range of values, different damping parameters do not alter the magnetization

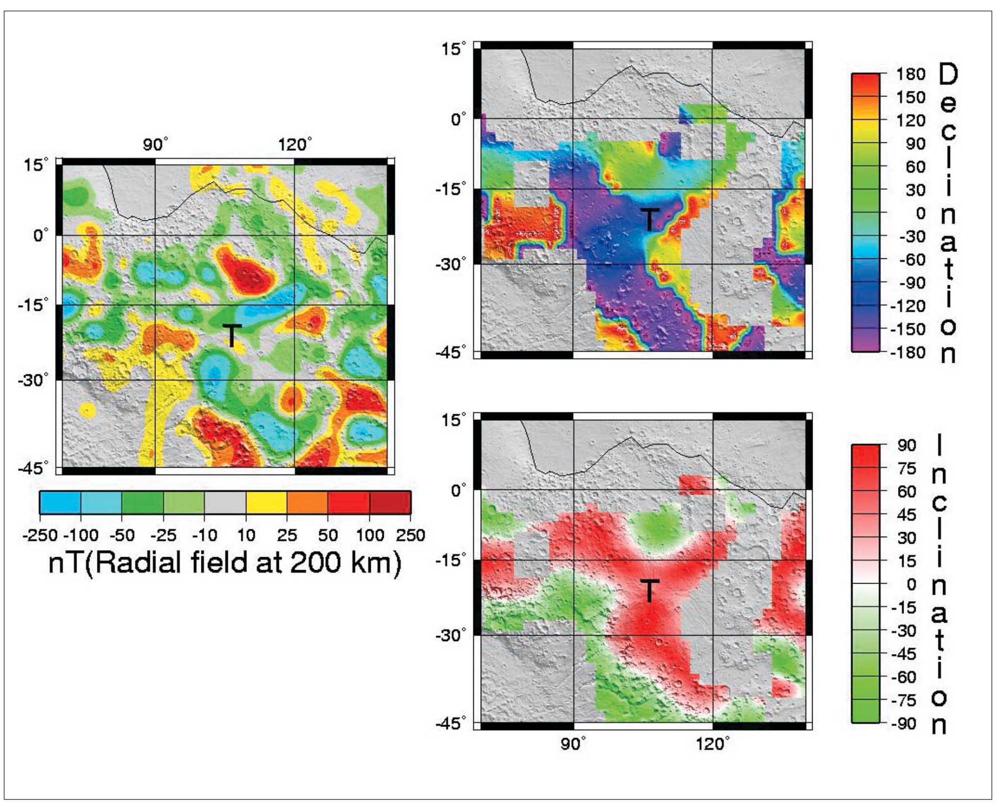

Figure 3. Close-up of the region around Tyrrhena Patera (T), showing the radial field component data leveled to 200-km altitude (left) and the magnetization model declination and inclination (right panels), superimposed on the MOLA topography (gray shaded relief). The solid line toward the top is the dichotomy boundary.

pattern, only its strength, which decreases as misfit increases. This robustness of the pattern of magnetization means that its declination and inclination can be reliably inferred, at least in areas where its strength is sufficiently large for these angles to be well defined. The declination and inclination, superimposed on the MOLA topography, are plotted in Figure 2, but only where magnetization strength exceeds a certain threshold, leaving gaps primarily in the northern hemisphere.

Figure 2 shows clear triple junction-like features in the more strongly magnetized southern hemisphere. Probably the best developed is centered over the Tyrrhena Patera at 21.4°S, 106.5°E (shown in detail in Figure 3) where a clear reversal from +90° to -90° inclination occurs, arranged along the "arms" of a triple. The Martian dynamo must have reversed at least once to produce this pattern, if the triple junction interpretation is correct. The first suggestion of such a triple junction-like feature on Mars (in the Valles Marineris region, east of the region in Figure 2) was made by French researchers Vincent Courtillot and Claude Allegre in 1975, based on Mariner 9 data. There is a large gravity anomaly associated with Tyrrhena Patera, recently interpreted as a high density magma chamber 275-300 km in width and at least 2.9 km in thickness.

Jafar Arkani-Hamed has produced forward models of 10 isolated magnetic anomalies, mainly in the northern hemisphere, as point sources of magnetization. From the pole positions of these models (assuming a centered axial dipole source), he showed that several are reversed, and clustered away from the poles of rotation. Our magnetization pole positions are stable as the data misfit is varied, and we have compared them with his. In a number of cases, they agree well—6 out of 10 are within 30° of his positions. Both his forward modeling and our inverse modeling provide evidence for reversals. The pole clustering away from the rotation poles may suggest plate tectonic movement (such that the site of the cluster was originally at a rotation pole), or a dynamo field that was either predominantly nondipolar or dipolar but not aligned along the rotation axis.

We have also produced models from all three components of the magnetic field, using the same methodology. The computational effort is significantly higher due to the larger number of data. The models are very similar to the example in Figure 1, but fit the data much worse (in a root-mean-square sense). This lends further support to the suggestion that external field contamination, known to affect the horizontal components more, is a primary source of unaccounted for noise in the data.

Our models show tantalizing suggestions of plate tectonics and magnetic field reversals on Mars, and possible nondipole field behavior. However, we need to improve the data set and its error budget, so that we can fit the data to within their expected uncertainties. We also need to improve the models, particularly near the poles, before we can draw conclusions with confidence. Fortunately, MGS data are still being acquired, and we have every reason to believe that these improvements are achievable in the near future.

Suggested reading. "Mars core and magnetism" by Stevenson (*Nature*, 2001). "The crust and mantle of Mars" by Zuber (*Nature*, 2001). "On magnetic spectra of Earth and Mars" by Voorhies et al. (*Journal of Geophysical Research*, 2002). "An altitude-normalized magnetic map of Mars and its interpretation" by Purucker et al. (*Geophysical Research Letters*, 2000). "Paleomagnetic pole positions and pole reversals on Mars" by Arkani-Hamed (*Geophysical Research Letters*, 2001). "Fluid core size of Mars from detection of the solar tide" by Yoder et al. (*Science*, 2003). TLE

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